

Reconciling the CDF Wjj and single-top-quark anomalies

Zack Sullivan and Arjun Menon

Department of Physics, Illinois Institute of Technology, Chicago, Illinois 60616-3793, USA

We demonstrate that there is no evidence of any Wjj excess or deficit within CDF data if a data-derived background estimation that includes single-top-quark production is used instead of a Monte Carlo estimate. Instead, when coupled with the CDF measurement of single-top-quark production, a more interesting anomaly exists within CDF data: namely, there are too many $W + 0$ b -tag and $W + 2$ b -tag events, and too few $W + 1$ b -tag events. As we previously predicted, there is no significant evidence of any of these anomalies in the $D\emptyset$ data set.

1. Introduction

Great excitement was caused by the observation by the CDF Collaboration of a large apparent peak in Wjj that was suggested in Ref. [1] to be the result of a Gaussian peak sitting on top of the Wjj continuum background. In Ref. [2], we demonstrated how an existing excess in the CDF measurement of single-top-quark production would translate into the Wjj signal region, and fit the apparent excess, assuming it was a fluctuation of single-top-quark production. We concentrated in that paper on single-top-quark production, rather than $t\bar{t}$ production, because of a statement in the CDF paper that the $t\bar{t}$ contribution had been fit to data, but single-top had only been modeled by Monte Carlo.

This proceedings constitutes a significant update to Ref. [2] that clearly demonstrates the excesses in Wjj and in the single-top measurements are the same. Unlike our paper, we are now able to show that no corrections to single-top are required to fit the data. What is less clear is whether the events are physically due to single-top, $t\bar{t}$, or most likely a combination of many things. While we do not solve all problems, we demonstrate these anomalies reside solely within the CDF data, and reclassify the issues as a result of an anomaly in the number of b -tagged jets in the Wjj sample.

In order to clearly identify where the real discrepancies exist, we first reexamine the data to learn more about the Wjj anomaly, and then show its resolution. In Section 2, we point out that the CDF data set strongly suggests that the excess is partly due to a feed down effect of the $W + 3$ -jet sample into the $W + 2$ -jet sample. The heart of this update is Section 3, where we refit the CDF data with single-top as extracted from data [4], and compare to the fit in Ref. [1]. Here we explore several problems with the original CDF fit that all disappear under the assumption the excess is pure single-top. We also demonstrate that an identical prediction for $D\emptyset$ perfectly fits their data set. Finally, in Section 4 we conclude by addressing the question again of whether the apparent excess is single top or something else.

2. $W + 3$ -jet feed down to $W + 2$ -jets

As additional tests have been performed on the CDF data set to try to pin down the source of the Wjj excess, we have attempted to place these results in context. In particular, one measurement by CDF provides an essential clue as to the source of the excess. In Fig. 1 we overlay two data sets on top of each other: the original Wjj sample from the CDF paper, and the CDF Wjj sample where the definition of a jet was loosened to $E_{Tj} > 20$ GeV from the original $E_{Tj} > 30$ GeV [3]. In addition, the P_{Tjj} cut is removed in the looser set.

When first looking at this figure, it seems that perhaps there is a mistake in the data. The bins with more tightly defined jets have systematically *more* events than the bins with more loosely defined jets above 100 GeV. If the looser jets were a super-sample, this would not be possible, and this would indicate a clear inconsistency. After some consideration, however, it is apparent the looser defined jets are only a *partial* super-set of the tighter jets. In particular, because this is an exclusive 2-jet final state, by lowering the threshold for jet acceptance, several 3-jet events that had a jet between 20–30 GeV are thrown away.

The conclusion is that, assuming this data is correct, a significant portion of the excess appears to be coming from proto 3-jet events that are sneaking in to the 2-jet sample because of the effectively weaker jet veto. This is consistent with the CDF check that a more inclusive sample (allowing in 3 jets) did not change the result, because the relevant 3-jet events were already there. As we'll see below, this is what we see in single-top as well.

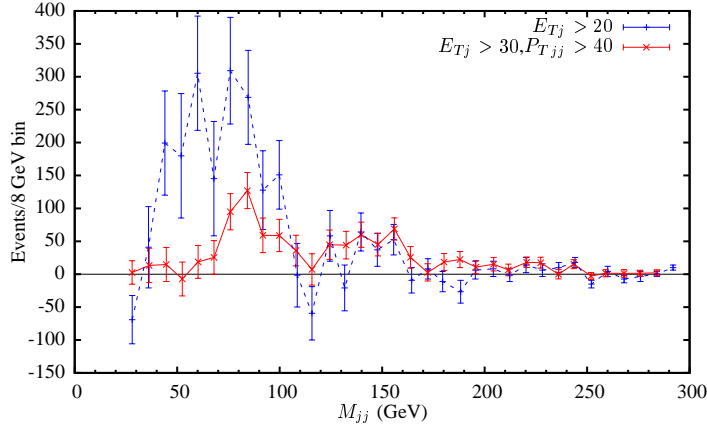


Figure 1: M_{jj} for Wjj , where jets are defined to have $E_{Tj} > 30$ GeV (solid red) and $E_{Tj} > 20$ GeV (dashed blue).

3. Refitting the CDF data

In order to track down what could have faked a peak in the 120–160 GeV, we investigated the influence of several effects: jet energy resolution, sensitivity to particular cuts, etc. In our initial paper [2] we thought we might need strong assumptions about these effects to explain what was going on. It has turned out we do not. After more thorough investigation we find that *absolutely no corrections* are required to explain the excess as anything but single-top. Hence, we hold off until Sec. 4 any mention of the role of jet energy resolution effects, etc., as we now find they are not needed.

Using shapes from pure vanilla MadEvent, and normalizations from the CDF fit to single-top, we can perfectly explain not only the excess between 120–160, but in fact the entire region 28–300 GeV. We find our fits solve several problems with the initial CDF fits that were not emphasized before, but indicate a more complex story than just an excess in the 120–160 GeV region. In Subsec. 3.1 we reexamine the CDF sample and point out some statistical problems with the CDF fit. We then add our estimate of single-top in Subsec. 3.2, and demonstrate the problems vanish. Finally, we show our fit to $D\bar{D}$ in Subsec. 3.3.

3.1. Re-examining the CDF fit

In order to make a quantitative statement about how top explains the excess, we start by extracting the data from Ref. [1] for three sources: the measured data, the WW/WZ diboson peak, and the rest of the background fit (which includes everything else: Wjj , $t\bar{t}$ fit to data, single-top from Monte Carlo, and other smaller components). We then proceed to look at the remainder of the data after subtracting all backgrounds from the measurement. The result appears in Fig. 2.

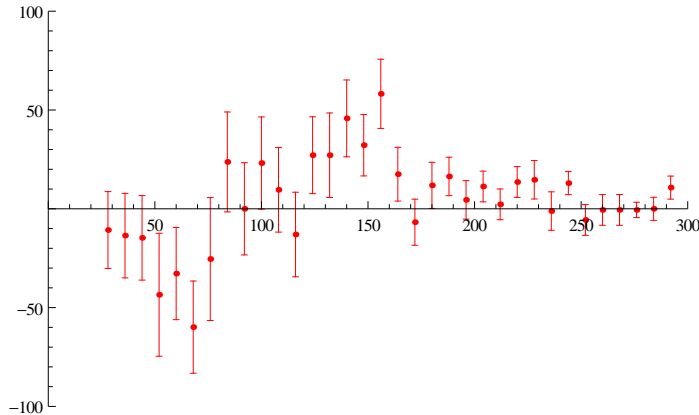


Figure 2: M_{jj} for remainder after subtracting all backgrounds from the data.

What is readily apparent from Fig. 2 (more so than Fig. 1 of the CDF paper which leaves in dibosons) is that there is a systematic problem with the M_{jj} shape across the entire spectrum, from 28–300 GeV. In particular, the *deficit* of events below WW/WZ threshold is more worrisome than the excess between 120–160 GeV. However, we see that the excess in fact exists everywhere from 84–300 GeV. Already we can perceive that we will want a broad kinematic distribution to fix this, but that is discussed in the next Subsection.

To explore this a bit more, we perform the χ^2 fit on the data we extract to quantify the quality of the background fit. When fitting over 28–200 GeV we get a $\chi^2/\text{d.o.f.} = 44.5/19$. It is not surprising the fit is poor, as it is already clear from Fig. 2 that the data does not follow a Gaussian statistical distribution. We emphasize this point in Fig. 3, where we plot the distribution of residual errors and compare it to a Gaussian. The data exhibits significant positive skew and kurtosis — i.e., there is a missing systematic effect. The CDF paper attempted to solve this by adding a Gaussian peak and refloating the background and signal fits. A simple count of the number of points above and below the fit with a Gaussian still shows a massive skew (14/30 points are at least 1σ above the fit) — hence, it will not be a good fit either. The need for exotic partial corrections disappears below, so we will not dwell on the Gaussian hypothesis.

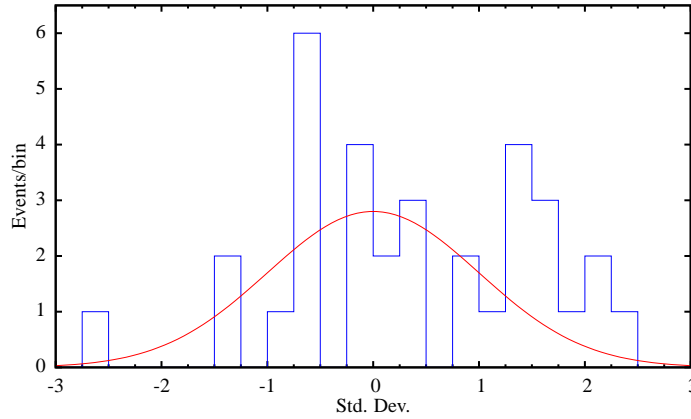


Figure 3: Distribution of error residuals in CDF fit compared to a Gaussian distribution.

In conclusion, it is clear that the backgrounds considered in the analysis do not fit the data, despite their normalizations being floated. As we are about to see, this is solved by adding single-top as extracted from data.

3.2. Adding data derived single-top

In order to quantify the effect of translating the CDF single-top measurement into the Wjj channel, we do the following: We run s -channel and t -channel single-top in MadEvent, producing both Wjj and $Wjjj$ final states. $Wjjj$ is an NLO correction to LO, but was separately extracted by CDF in their single-top fit. We apply all of the same cuts as the CDF paper, and produce M_{jj} for each sample. In the case of $Wjjj$, many events are killed by the jet veto, but not all. In Fig. 4 we show the shapes for each channel, based on the number of jets initially produced. Note the shapes are all about the same. In fact, under unit normalization, the shapes are nearly identical, with 2-jet s -channel slightly harder above 200 GeV, and 2-jet t -channel slightly softer below 80 GeV.

The distributions in Fig. 4 are normalized to Ref. [4], and the supporting web page, which *did not* find the predicted Standard Model-like ratio of these modes. In particular, t -channel production was extracted in the CDF analysis as being $0.6\times$ the expected size in 2-jets, and $2\times$ in 3-jets, and s -channel production was found to be too large by a factor of 3.8 in 2-jets, and 2.7 in 3-jets. An essential point is that this is the same raw data set that Wjj was drawn from — the same trigger, and almost the same integrated luminosity.

We want to see what the CDF single-top data set predicts for Wjj , so we do the following:

1. We first remove a Standard Model size prediction for single-top from the CDF background estimate we extract from their paper (call this Wjj_r for residual). We use NLO K -factors (which have been checked in the past after cuts) of 1 for t -channel and 1.5 for s -channel [5].

2. We refit the data using a minimal χ^2 test on three samples:

- (a) $a \times Wjj_r$ — all backgrounds as predicted by CDF except for dibosons and single-top.

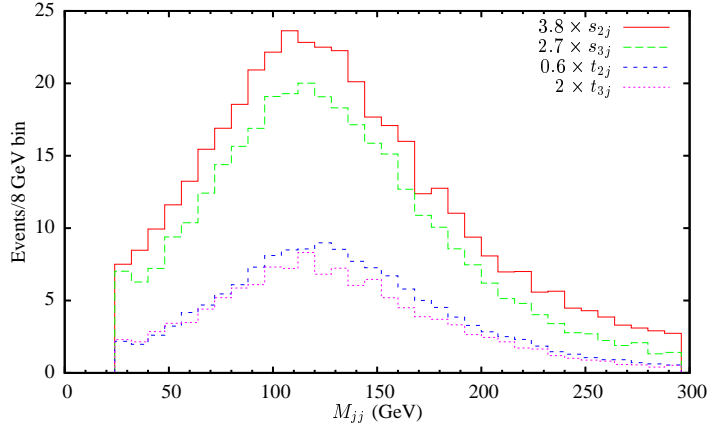


Figure 4: s - and t -channel contributions to Wjj after all cuts from initial 2-jet and 3-jet samples multiplied by K -factors extracted from CDF single-top data.

(b) $b \times VV$ — WW/WZ dibosons.

(c) $c \times \text{single-top}$ — where we add $0.6 \times t_2 + 2 \times t_3 + 3.8 \times s_2 + 2.7 \times s_3$ to match the ratios extracted by CDF.

3. Compare a , b , c to 1, and to the CDF fit.

Before we show the results, a word on these fits. While we have chosen to use the ratio extracted from CDF, we immediately notice that the deficit in t -channel 2-jet is largely cancelled by the excess in t -channel 3-jet, leaving us mostly sensitive to additional s -channel. However, as the shapes are all about the same, and the quoted CDF single-top errors are large (50–80%), it is easily conceivable that there could be a different mixture in the sample. We choose the ratio observed by CDF to perform our fit, but in the end, we are really just fitting a shape. It turns out the normalization is also perfectly consistent.

In Fig. 5 we compare the CDF fit to the data with the the new best fit using $1.4 \times$ single-top as extracted from data. It is clear that the fit including single-top is now consistent everywhere from 28–300 GeV. Our fit of the CDF $\chi^2/\text{d.o.f.}$ of 44.5/19 improves to $\chi^2_{\text{new}}/\text{d.o.f.} = 25.7/26$ (we fit 30 points with 3 variables). Our best fit finds we need $0.91 \times$ as much Wjj_r and WW as was required in the CDF fit, but as those normalizations were floated in the CDF fit as well, it is not a surprise.

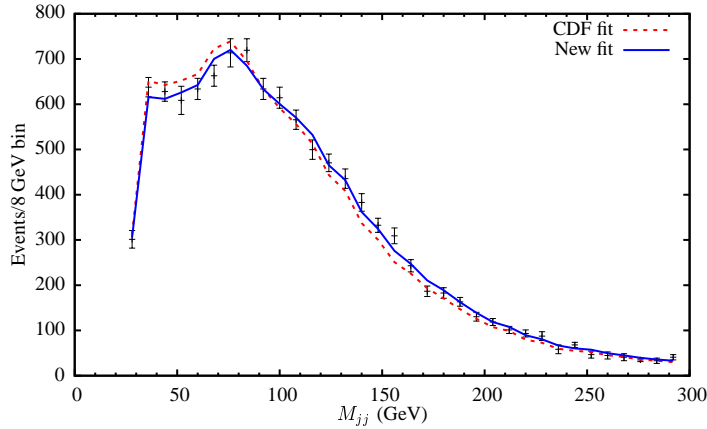


Figure 5: Comparison of Wjj data with CDF fit (red dashed), and fit with single-top extracted from CDF data (blue solid).

To stress that the residual is statistically removed, we compare the background subtracted data before and after the new fit in Fig. 6. The red line represents the central values of the original baseline CDF subtracted data, and the blue error bars represent what remains after subtracting the new background fit. The systematic deficit(excess) below(above) WW is gone.

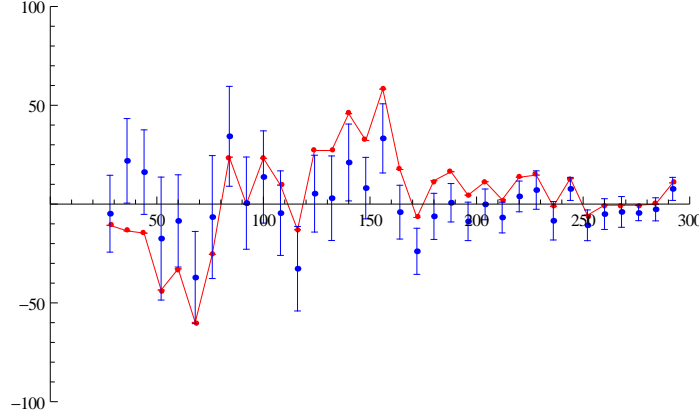


Figure 6: Comparison of data minus background with the CDF fit (red line), and the new fit using single-top extracted from CDF data (blue error bars).

Before, the distribution of residual errors in the CDF fit did not have an obvious statistical distribution. We see in Fig. 7 that after adding data-derived single-top, the distribution of errors is a textbook sampling of a Gaussian distribution. Hence, we have solved both the normalization issue, but, more importantly, all shape issues from, 28–300 GeV. We consider this extremely strong evidence that the excesses in the CDF single-top sample and in Wjj have the same origin. The Wjj excess is perfectly explained by the shape of single-top. Whether this *is* single-top, we'll address more below, but the excess in Wjj is almost certainly a kinematic shoulder, and not a resonant particle.

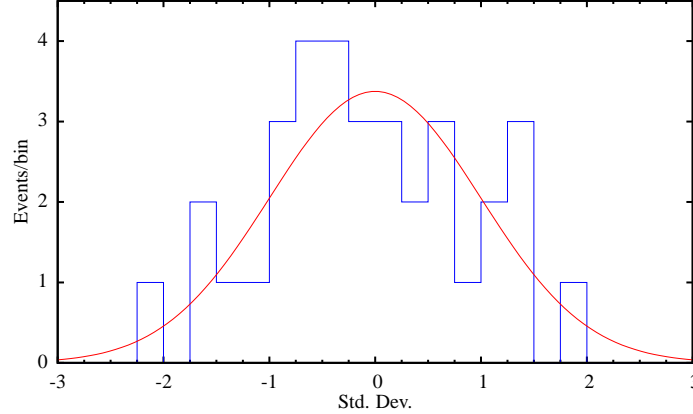


Figure 7: Distribution of error residuals in fit compared to a Gaussian distribution.

In case some are uncomfortable with using $1.4\times$ the central value of extraction of single-top, we point out this is only 0.5σ above the central value. Nevertheless, we also show in Fig. 8 that using $1.0\times$ the central value gives $\chi^2/\text{d.o.f.} = 26.0/26$. Interestingly, almost any increase above the baseline Monte Carlo prediction for something with the shape of single-top dramatically improves the $\chi^2/\text{d.o.f.}$.

3.3. Comparison with $D\bar{0}$

In our paper [2] we made a prediction that $D\bar{0}$ would see (at most) a very small excess in Wjj because their early single-top data agreed almost perfectly with the Standard Model prediction. Since that time, $D\bar{0}$ has released a paper [6] claiming that their data is consistent with no excess. While that is statistically true, $D\bar{0}$ actually does have a modest excess in t -channel production. Specifically, $D\bar{0}$ has found $1.28\times$ t -channel, and $0.94\times$ s -channel in Ref. [7]. Strangely, this small excess goes in exactly the *opposite* direction as the CDF excess. However, we thought it would be useful to use the same procedure to check our prediction for $D\bar{0}$.

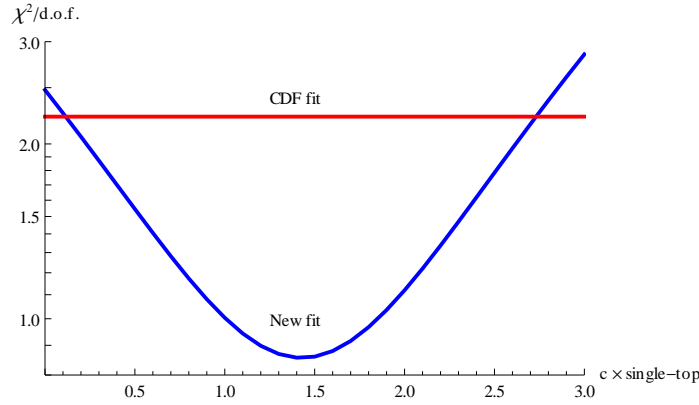


Figure 8: Comparison of the $\chi^2/\text{d.o.f.}$ we find from fitting the published CDF data (including $1\times$ the Standard Model prediction of single-top), and from adding $c\times$ single-top as extracted from the CDF data set.

The result is that the $\chi^2/\text{d.o.f.}$ goes from 26.4/24 to 25.3/24 with no change to the required amount of WW ($b = 1$), slightly less Wjj_r ($a = 0.97$), and $1.5\times$ single-top as extracted from the $D\bar{0}$ measurement. Not much was expected or needed, but interestingly, the fit is best with almost the same increase in single-top as CDF. Obviously this is well within errors. In Fig. 9 one can see that above WW threshold adding a little more single-top is just as consistent as that predicted by the $D\bar{0}$ Monte Carlo. Hence, this is a suggestive consistency check, but is not statistically powerful enough to help understand the CDF anomaly.

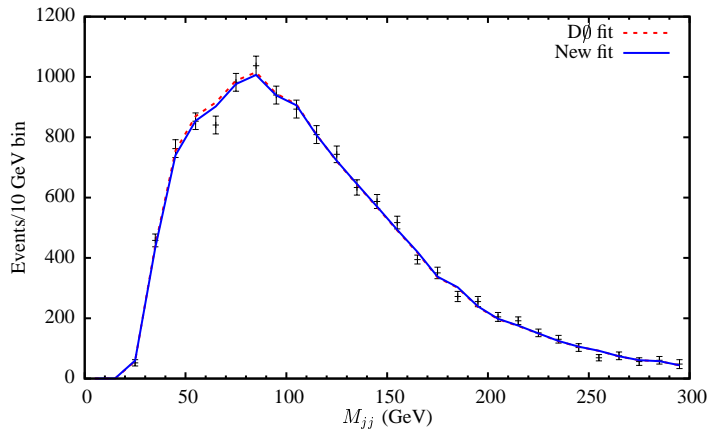


Figure 9: Comparison of $D\bar{0}$ data with and without additional single-top.

4. Is it single-top?

We have been very careful to state that the CDF excess in Wjj is fully explainable by something with the kinematic shape of single-top, and normalization that fits the criteria of the CDF single-top measurement excess, but we have been careful not to claim we can prove it *is* single-top. The burning question is: what is it?

Initially, we made it clear we were not considering $t\bar{t}$ production solely because the CDF paper claimed to have fit it in data, and properly accounted for it. Given our observation that 3-jet events feeding into 2-jet events is playing at least some role, this may need to be revisited. How well do we understand the sample of $t\bar{t}$ under these exact cuts? We cannot answer that theoretically. It requires deep access to the internal procedures used to fit $t\bar{t}$ in the first place.

Once thing we can show, however, is that the some of the kinematic shapes in $t\bar{t}$ are compatible with the single-top shape. There are *many* $t\bar{t}$ final states that could be feeding into the Wjj analysis. In Fig. 10 we choose to focus on one: $t\bar{t} \rightarrow b\bar{b}e\tau$. This process could be playing a role, as τ s are often reconstructed as jets.

Further, they represent only one particle to miss. $t\bar{t}$ certainly has 2 b jets, which an excess of could help partially explain the anomalously large sample of 2 b -tag events in the single-top analysis.

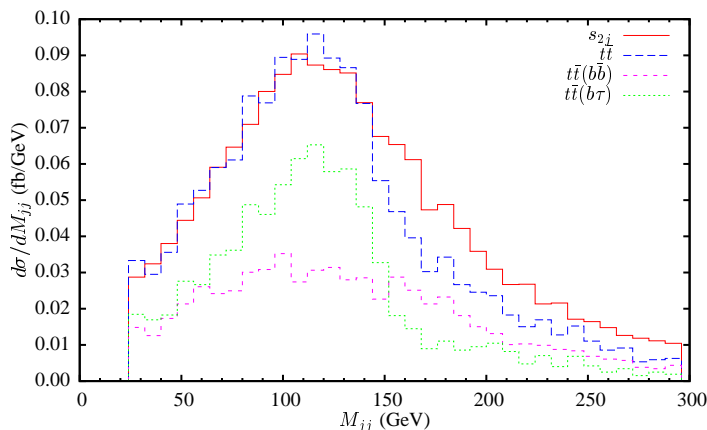


Figure 10: M_{jj} for $t\bar{t} \rightarrow b\bar{b}e\tau$ and s -channel single top into $b\bar{b}e\nu$.

In Fig. 10, we split out the contributions to Wjj from bb and $b\tau$ to point out that the shapes are significantly different. The shape of bb is almost identical to that of s -channel production (though $t\bar{t}$ is intrinsically smaller in this channel, there are other possible decay modes). $b\tau$ falls sharply near 150 GeV. It seems likely that a fit that allowed some additional $t\bar{t} \rightarrow b\bar{b}e\tau$ would also fit the data. However, there are not enough degrees of freedom in the data we have to trust such a fit.

So where does this leave the question? The answer is likely that the excess is due to a combination of top-quark initiated backgrounds plus something else not understood. It is in the part that is not understood that we feel is where the emphasis should be placed. Having tied together the single-top measurement anomaly and the Wjj excess leaves us with a strange quandary: The CDF Wjj data has too many 0 b -tag events, too many 2 b -tag events, and not nearly enough 1 b -tag events in this simple kinematic region. If anything, one would expect that a missed b -tag would lead to an excess in the 1 b -tag sample at the expense of the 2 b -tag sample. The size of the effect seems large to be purely statistical, but that is a detail of the data set that CDF will have to study internally. Nevertheless, we feel the solution to this whole conundrum is tied to explaining this more general discrepancy.

As a final comment on the b -tag issue: We had suggested looking for excess b -tags in the Wjj sample early on in this investigation. The only CDF analysis and plot we have seen claims that b 's cannot be playing a role because the number of b tags between 120–160 is fractionally the same as outside that region. Given that a single-top excess exists across the entire 28–300 GeV region, that is exactly what we would have predicted. The question is one of total absolute rate — not relative rate in a small mass window.

Given our success in reproducing the Wjj excess without any alterations to the shape or normalization of single-top (as extracted from CDF data), it is not necessary to play with jet energy scale (JES), etc. However, for completeness, we include a comparison of the shapes between the MadEvent s -channel shape and with what might be called the “maximally distorted distribution” (MDD) in Fig. 11. In the MDD we make the following modifications: multiply the jet energy scale (JES) by 1.1, multiply the missing energy scale by 1.16, lower the cut on \cancel{E}_T to $\cancel{E}_T > 20$ GeV from 25 GeV, and lower the cut to $P_{Tjj} > 20$ GeV from 40 GeV. The missing energy cut and energy shift are made because they are sensitive to slightly different physical effects. The change in the cut on P_{Tjj} is made because, as we pointed out in Ref. [2] this distribution is not all that well modeled by leading order.

The conclusions are that shifts in JES, or misprediction on the shape of P_{Tjj} can both push the peak of the top backgrounds to slightly higher M_{jj} values; and allowing uncertainty into the missing energy measurement can increase the normalization. Neither is required, but does give some sense of the inherent uncertainties in the shapes and normalizations fit in the data. There are additional theoretical uncertainties on top of these, but they are a minor issue compared to understanding the origin of the significant deficit of t -channel production and excess in s -channel production in that 3.2 fb^{-1} data set.

In conclusion, if a data-derived background estimation including single-top-quark production is used to measure Wjj we find that there is no evidence of any excess or deficit within the CDF data set. Instead, a more interesting anomaly exists within CDF data: namely, there are too many $W + 0$ and $W + 2$ b -tag events, and too few $W + 1$ b -tag events. Hopefully, an understanding of the origin of this observation will explain the both

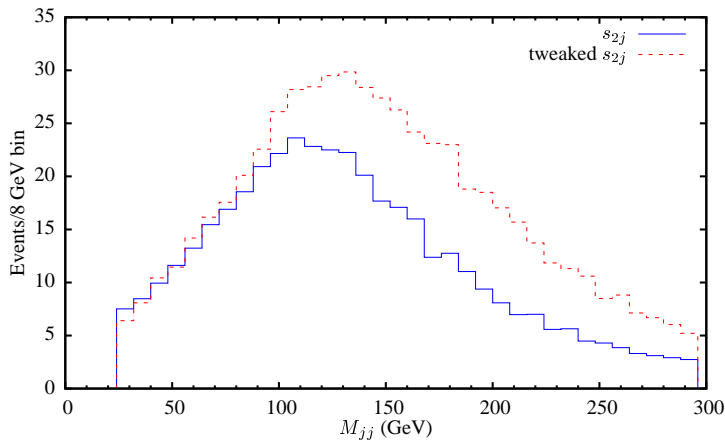


Figure 11: Comparison of vanilla LO s -channel and s -channel distorted by tweaking measurement uncertainties.

the apparent Wjj and single-top-quark anomalies in the CDF data set.

Acknowledgments

This work is supported by the U. S. Department of Energy under Contract No. DE-FG02-94ER40840.

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